PART III
EVOLVED STARS

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THE GALACTIC DISTRIBUTION OF OH/IR STARS

H.J. Habing+)

Joint Institute for Laboratory Astrophysics - University of Colorado and National Bureau of Standards
Boulder, Colorado

I. THE STARS

1. Observational opportunities and goals.

In 1967 Wilson and Barrett (1968, 1970) discovered that some long period variables, very red and apparently very late type stars, emit OH microwave line emission that is especially strong in the 1612 MHz line at 18 cm. At present some 65 such OH-emitting stars have been identified - for a recent compilation see Bowers and Kerr (1977, M giants) and Baudry et al. (1977, M supergiants). Several stars show maser emission in H_2O and SiO as well. At this colloquium Winnberg will review the present status of our knowledge of these stars.

The first so discovered stars were rather strong radio emitters, and yet they were at appreciable distances from us. Therefore it became obvious that such stars can provide an opportunity to observe and to study the galactic distribution and the kinematics of late type and probably well evolved stars. Since this will be done at radio wavelengths, interstellar extinction will not prevent us from seeing a large part, if not all, of the Galaxy. Such a study has to be compared with, e.g. those of the distribution of H I, of H II (indicative, probably, of the distribution of OB stars), of CO clouds and of supernova remnants as reviewed recently by Burton (1976). Since the objects are well evolved stars, the results of the surveys should also be compared with the galactic distribution of planetary nebulae (Minkowski, 1964). Finally, because in the solar neighbourhood M type giants contribute significantly to the recycling of matter, recycling could perhaps be better understood also else-

+) on leave of absence from the Sterrewacht, University of Leiden, The Netherlands.

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where in the Galaxy (e.g. in the galactic centre) by observing the late type giants.

Here I want to review several studies in the 1612 MHz OH line that aimed at the discovery of these late type stars, with the goal of obtaining their galactic distribution. Most of these studies have recently been completed and a few have not yet been published.

2. What kind of stars?

This review will be dealing with sources which have been found only through their OH emission. Most of these sources have not yet been identified at other wavelengths ranges. However, it is instructive to start with a discussion of what we know about those optically well confirmed stars that show OH emission (see also the reviews at this colloquium by Winnberg and by Merrill).

2.1 Stars that show OH emission are all very red, long period variables with thick circumstellar shells. From the presence of certain molecular bands at 2 to 4 μm and the absence of other bands (see e.g. Merrill, this colloquium) one concludes that all have M-type spectra. S- and C- type long period variables never show OH maser emission. From the available data it appears that the following characteristics make it more likely to detect OH-emission from a star (see Winnberg and Merrill at this colloquium):

i) Later spectral type (M5 to M10)

ii) Longer period ($P > 300^{d}$)

iii) Smaller ratio of rise time of lightcurve compared to decline time

iv) Stronger infrared excess.

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The OH emitting stars are all giants and supergiants, i.e. well evolved stars. What are their progenitors? What are their masses and what are their ages? For an answer to these questions one should perhaps rely on an analysis of the stellar motions, since the evolution tracks in the red giant phase is rather poorly known. The thorough analysis by Feast (1963) shows that red giants appear to consist of stars with widely different population characteristics, but that these characteristics correlate very well with the stellar period. Generally the stars appear to be younger, the longer the period. For example, Feast suggests that stars with larger periods ($P > 350^d$) originate from 2.5 $M_\odot$ stars and that they have an age of 5×10^8 yr or younger. While these numbers probably require some revision, the general conclusion is probably applicable to the OH stars: OH emitting stars have long periods and they probably belong to the youngest M giant population.

The OH emission of M type long period variables may occur in three lines belonging to the ground state: at 1612, 1665 and 1667 MHz. Intrinsically the strongest sources appear to have dominant emission in the 1612 MHz line. When the 1612 MHz line dominates, it usually shows a very characteristic line profile (Fig. 1a) consisting of two asymmetric peaks separated over a distance ΔV. After much discussion on the structure of this line profile there are now rather convincing arguments (see e.g. Winnberg and at this colloquium, 1976) to assume that the stellar velocity is half way between the two peaks and that the peaks correspond to two regions in an expanding circumstellar envelope, namely the regions closest to us and farthest away. The

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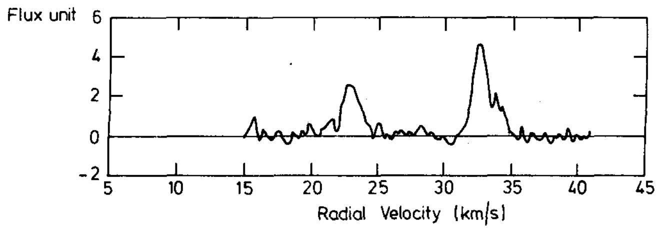

Figure 1a. *1612 MHz OH emission line profile of RR Aql, according to Wilson and Barrett (1970).*

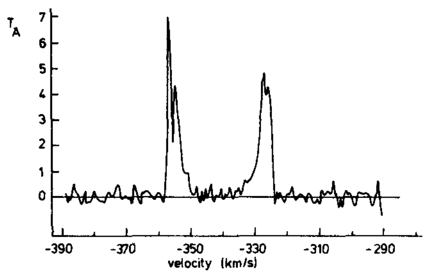

Figure 1b. *1612 MHz OH emission line profile of OH 0.33-0.193 near the galactic centre.*

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total flux density of the OH profile varies in time in the same direction and almost simultaneously with the optical and infrared variation (Harvey et al., 1974). A potentially important property of the OH emission is that ΔV appears to be correlated with the infrared colour index and with the period of the star - large ΔV (40 to 60 km s^{-1}) corresponds to long periods (500 to 900 days) (Dickinson et al., 1975). Finally, a promising pumping model for the stellar 1612 MHz maser has been proposed by Elitzur et al. (1976). Pumping of the masering OH levels is provided by 35 μm photons, that are being produced in the circumstellar dust shell. Since the 1612 MHz maser appears to be saturated, it is possible that the limited supply of 35 μm photons restricts the luminosity of the OH maser (see section 4).

2.2 Let us now turn to those unidentified OH sources that have been detected because of their characteristic 1612 MHz line profile (figure 1b). I assume that two additional OH criteria have also been fulfilled: the source is a point source; the flux density of the source varies on a time scale of a few months. What is the chance of identifying such a source at other wavelengths and to what kind of objects do they correspond? Quite recently Schultz et al. (1976) and Evans and Beckwith (1977) identified about 20 such OH sources with IR point sources. In all cases the close coincidence in position and the correlation between the time variation of the OH and IR radiation provide very strong evidence that the OH and the IR sources are spatially associated (see also Sherwood, this colloquium). Evans and Beckwith, who had the best observational possibilities, identified all six OH sources that they had on their

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search list. This 100 percent success rate is strong support for the hypothesis that all OH sources satisfying the three criteria mentioned before, are also IR pointsources - hence their name "OH/IR stars".

At this moment very little is known about the detailed IR spectra of the OH/IR stars. However, new IR measurements are continuously made and knowledge is rapidly increasing. Merrill (this colloquium) discusses a few cases and concludes that, again, the OH/IR stars consist of M type stars surrounded by circumstellar shells. The only difference with the M type stars discussed earlier appears to be qualitative: the dust shell is probably thicker for the OH/IR stars than for more normal M type stars. For example Merrill (this colloquium) suggests that OH 26.5-0.6 (AGL 2205) may consist of a M type star surrounded by a dust shell with a thickness corresponding to $A_v \approx 105^m$!

3. The distance of the OH/IR stars.

To derive the galactic density distribution and to study galactic kinematics, one should be able to determine the distances of the OH/IR stars. In principle, two different methods are available: a photometric and a kinematic method. In the latter, one uses the radial velocity to guess a distance. Since galactic kinematics are a goal, the photometric method is preferable. In this method one predicts the absolute luminosity L and then one derives the distance from the apparent luminosity - from either the IR or the OH luminosity. Spectral observations in the IR probably offer the best opportunity to assign an absolute luminosity to the

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object, because molecular bands can be very sensitive to gravity effects - for example Merrill (this colloquium) draws attention to such variation of a band of H_2O at 1.9 μm and one of CO at 2.3 μm. Another characteristic that perhaps is correlated with luminosity is ΔV, since ΔV is correlated with P and a correlation between L and P is expected a priori.

However, at present we have no calibrated absolute luminosities available nor do we have a well established spectral criterion to assign a luminosity class. Concerning the IR-luminosities, an interesting point has been brought forward by Evans and Beckwith (1977). They derived apparent bolometric luminosities for six OH/IR stars and then they noted that, if these stars are all placed at their near kinematic distances, the resulting absolute bolometric luminosities are surprisingly similar.

An interesting attempt to derive an OH-luminosity function has been made by Johansson et al. (1977b) - although I think that their end result is still unreliable. Johansson et al. found that the velocities of the OH/IR stars are determined largely by galactic rotation. They therefore determined the distance to each star from its radial velocity in the same way as used to be followed in the 21 cm line. This distance is ambiguous: one finds a near and a far kinematic distance, each of which is equally probable, except for the fact that a star at the far distance has a larger chance of being below the detection limit. This fact can be accounted for. The end result by Johansson et al. (1977b) is an OH-luminosity function that resembles a very narrow gaussian. This result seems unreliable, because a much larger spread in luminosity is expected (see further on). A possible reason for the narrowness is that Johansson et al.

(1977b) ignored random velocity deviations from circular rotation. These velocity deviations can be quite significant and will lead to an increase in the width of the luminosity distribution. It would appear worthwhile to repeat the calculation, under the assumption of a gaussian random velocity distribution with a dispersion of the order of 30 km s^{-1}.

Another way to obtain the OH luminosity function is to consider the apparent luminosities of the OH/IR stars at the galactic centre because they are all at the same distances. These stars can be distinguished from nearby OH/IR stars by their velocities (see section 10). The results of such an approach to the luminosity function are not yet available. However, already two problems present themselves: First, there are indications that the OH/IR stars at the galactic centre belong to a different population (Baud, this colloquium). Second, the OH/IR stars may suffer partial extinction by foreground molecular clouds.

A relevant argument concerning the OH luminosity can be derived from the OH pump model proposed by Elitzur et al. (1976). The OH maser appears to be pumped by 35 μm photons and, since the masers appear saturated (Harvey et al., 1974), the number of 35 μm photons probably limits the OH luminosity. Since the 35 μm photons are emitted in the long wavelength tail of the circumstellar dust radiation (c.f. the spectra presented by Merrill and Sherwood), the 35 μm flux, and hence the OH flux, is expected to differ considerably from object to object. These differences will be determined mainly by the total mass of the dust shell.

The 35 μm flux density will limit the OH flux only when enough OH molecules are present in the circumstellar shell. This may not always be the case. Goldreich and Scoville (1976) have discussed the chemical composition of the expanding circumstellar envelope of late type giants. They suggest that OH cannot exist in this envelope because it recombines very quickly with H_2 to form H_2O. The fact that OH masers nevertheless occur must be due to a process that dissociates the H_2O. But the only process that they can think of as operative, is dissociation of H_2O by the interstellar UV-field. Consequently OH masers will occur only where the interstellar UV radiation field is sufficiently strong, i.e. close to the galactic plane. This argument can therefore provide a very serious selection effect in the survey results, which I will call the Goldreich/Scoville effect.

Summarizing this section, it appears that we do not yet know the absolute OH and IR luminosities. But several ways are open to obtain values for these quantities. The possible existence of the Goldreich/Scoville effect may limit the detection of OH/IR stars to those close to the galactic plane.

4. Surveys completed and underway.

The first systematic scanning of a significant fraction of the sky was made by Johansson, Andersson, Winnberg, Goss (1977a, 1977b) with the Swedish 25m Onsala telescope and by Caswell and Haynes (1976) with the Australian 64m telescope at Parkes. Recently several other surveys have been undertaken - see Table 1 and Figure 2. In

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Galactic surveys aimed at the detection of OH/IR stars (as of July 1977)

interval in ℓ	interval in b	interval in V ($km\ s^{-1}$)	3σ noise fluctuations (f.u.)	number of new stars found	remarks	instrument and size	observers	publication
$18° \le \ell \le 51°$ $(26 \le \ell \le 36$ $30 \le \ell \le 32$	$-1° \le b \le +1°$ $-2° \le b \le +2°$ $-4° \le b \le +4°)$	$-30 < V < +200$	0.6	57		Onsala, Sweden 25 m	Johansson, Andersson, Goss, Winnberg	A & A 54, 323 A & A Suppl. 28, 199
$353° \le \ell \le 30°$ (only a few small areas)	$-4° \le b \le +4°$	$-225 < V < +225$	1	7	pilot survey	Green Bank, U.S.A. 43 m	Kerr, Bowers	A & A 36, 225
$15° < \ell < 230°$	$-3° < b < +3°$	$-200 < V < +200$	1.5	≈40		Green Bank, U.S.A. 91 m	Bowers	Thesis, Univ. of Maryland 1977
$10° \le \ell < 165°$ $(10 \le \ell \le 30$ $30 \le \ell \le 40$ $40 \le \ell \le 65$	$-2° \le b \le +2°$ $-4° \le b \le +4°$ $-3° \le b \le +3°$ $-2 \le b \le +2°)$	$-225 < V < +225$	0.9	≈50	area does not cover that observed at Onsala	Dwingeloo, the Netherlands 25 m	Baud, Habing, Matthews, Winnberg	unpublished
$358° \le \ell \le 10°$	$-0\overset{\circ}{.}5 \le b \le +0\overset{\circ}{.}5$	$-450 < V < +450$	0.3	31		Effelsberg, W. Germany 100 m	Winnberg, Matthews, Baud, Habing	unpublished
$(\ell^2 + b^2)^{1/2} < 0\overset{\circ}{.}5$		$-450 < V < +450$	0.01	≈15	"deep survey"	Effelsberg, W. Germany 100 m	Winnberg, Matthews, Baud, Habing, Tersides	unpublished
$0° \le \ell \le 3°$	$-2° \le b \le +4\overset{\circ}{.}5$	$-450 < V < +450$	0.7	7		Green Bank, U.S.A. 43 m	Baud, Matthews, Winnberg, Habing	unpublished
$326\overset{\circ}{.}6 < \ell < 340°$	$-0.20 < b < +0.20$	$-230 < V < +130$	0.75	14		Parkes, Australia 64 m	Caswell, Haynes	M.N.R.A.S. 173, 649
$340° < \ell < 358°$ $(355 < \ell < 358°$	$-0.40 < b < +0.40$	$-230 < V < +130$ $-450 < V < +450$	0.32	≈45		Parkes, Australia 64 m	Caswell, Goss, Haynes, Mebold	unpublished

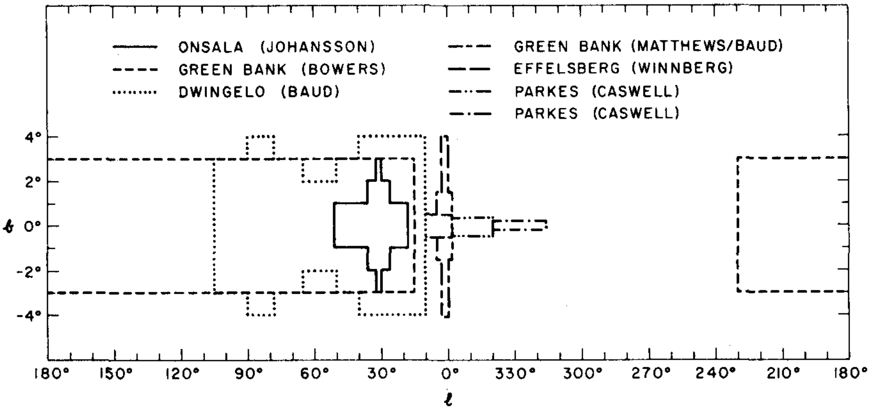

Figure 2. Coverage of the sky by various OH surveys. (see Table 1).

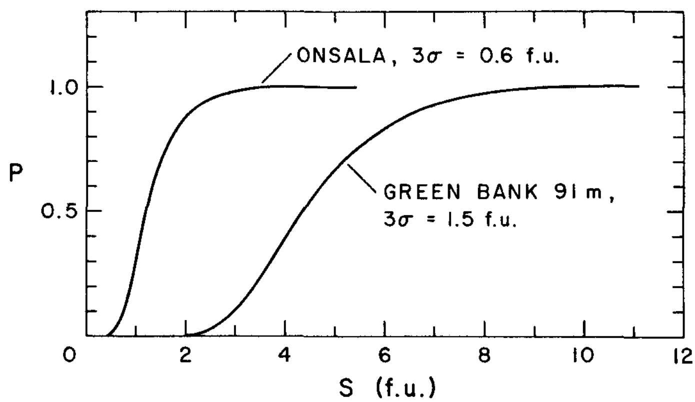

Figure 3. Probability of detection of an OH/IR star in two surveys.

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most cases the observations have been completed but the results have not yet been fully analyzed.

Surveys are made by pointing with the telescope at successive directions along the galactic plane. Integration times per position are typically 5 to 15 minutes. Since a radiotelescope is basically a light collector one measurement gives the total signal in the field of view, or antenna main beam, which varies from 7.5' for the 100m Bonn telescope to 31' for the 25m Onsala and Dwingeloo telescopes. This signal is spectrum analyzed over a band usually 200 to 400 km s^{-1} wide. The spectrum contains noise with an r.m.s. value σ, and for the surveys in Table 1, 3σ varies from 0.1 to 1.5 f.u. for a point source at the centre of the antenna beam. Experience shows that at 1612 MHz 50 or 60 percent of the signals have the very special signature of an OH/IR star - see Figure 1. The remaining 50 to 40 percent of the signals, usually the weaker ones, are sometimes connected with H II regions, sometimes with molecular clouds and a significant fraction may actually correspond to weak OH/IR star emission where, however, only one peak is barely strong enough to show up. In the galactic centre region the observations are plagued by the presence of a strong radiosource (Sgr A) and - at low velocities-strong absorption lines of OH in molecular clouds.

Let us discuss briefly the surveys that have been made. In terms of sky coverage (Fig. 2) one notes that most of the galactic plane has been covered. Coverage in the b-direction is small, but in view of the narrowness of the source distribution it is probably adequate - at least at $\ell < 10^{\circ}$, including most of the southern sky, a broader

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b-coverage is desirable. The extent in longitude is quite adequate since almost all sources are found within 40^{o} from the galactic centre . The ultimate sensitivity of a survey, expressed in the r.m.s. noise value σ is an important item, because many sources are found near the sensitivity limit. The deeper one goes, the more sources one finds and one should keep the goal of improving sensitivity until the whole Galaxy can be penetrated. However, in view of receiver developments and availability of large telescopes it appears to me that we have reached practical limits and I do not foresee in the near future new *large* scale surveys that will reach detection limits significantly weaker than, e.g., those of the Parkes and Onsala surveys. Note, that from the surveys in Figure 2 the one with the largest sky coverage (Bowers, 91m Green Bank Survey) has also the poorest sensitivity limits.

An important point in surveys is the completeness of the search. First, one should realize that the OH/IR stars are variable in time, so that surveys should be repeated after a time interval of at least 6 months - this is seldom done. Second, for a really thorough discussion of the galactic distribution of the sources the effect of limited sensitivity should be kept in mind. What is the chance, P, that a source of given peak flux density S is actually recognized? This problem has been studied by Johansson et al. (1977b) and by Bowers (1977), and the result is shown in Figure 3. Optical observers will no doubt recognize the value of such a curve in evaluating the results of a survey.

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In summary I feel that radioastronomers have reacted adequately to the challenge of doing stellar galactic research with radio telescopes. What could be done in terms of surveys has been done, and need only be completed. The emphasis will from now on lie on the identification of the OH sources with infrared counterparts, and on a study of the time variation of the sources.

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II. STARS OUTSIDE THE CENTRAL REGION OF THE GALAXY

The various surveys mentioned in part I of this review have given us over 200 new maser sources of the OH/IR star type. Plotting these sources in an (ℓ,b) diagram the result is seen in Figure 4 (southern hemisphere data were incompletely known to me and have not been included). Two properties of Figure 4 stand out: (a) the distribution is thin in latitude, i.e., the stars show a strong concentration to the galactic plane; (b) the stellar density decreases strongly between $\ell = 30^{\circ}$ and $\ell = 50^{\circ}$. Both properties will now be discussed in more detail.

5. Distribution of OH/IR stars in latitude.

Figure 5 is a histogram of the starcounts in latitude intervals $0\overset{\circ}{.}5$ wide. The diagram is due to Bowers (1977) but it agrees with that of Johansson et al. (1977b ; they had fewer stars available) and with my own compilation including the most recent surveys. The distribution is very narrow: Figure 5 contains 67 stars, of which 35 are within $0\overset{\circ}{.}5$ degree from the galactic plane. Apparently the stars are very much confined to the galactic plane. However, this conclusion may turn out to be unjustified, if the Goldreich/Scoville effect occurs. For, if the interstellar UV radiation is required for the production of OH, the observed latitude distribution of the OH/IR stars may be simply a reflection of the latitude distribution of the interstellar UV radiation field. In the following discussion I will assume that the Goldreich/Scoville effect does not influence the results, but the possibility that it does should be kept in mind.

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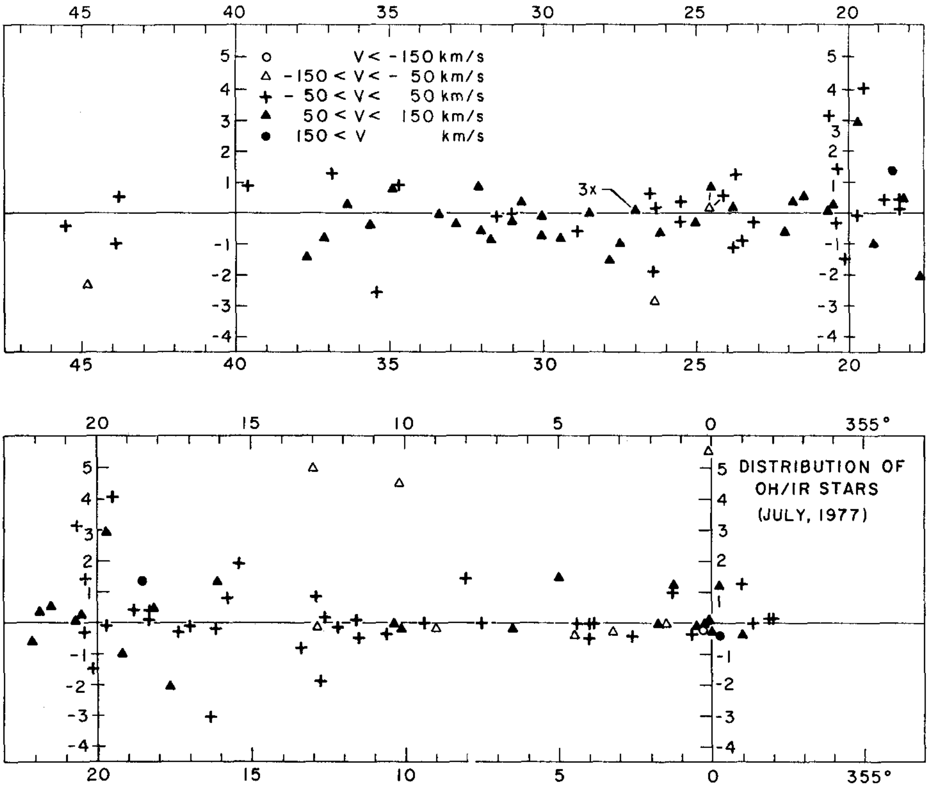

Figure 4. *Distribution in the sky of all OH/IR stars unidentified as of July 1977.*

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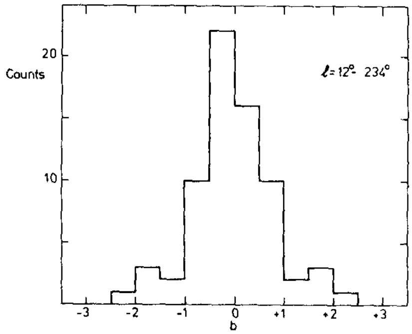

Figure 5. *Distribution of OH/IR stars in latitude, according to Bowers (1977).*

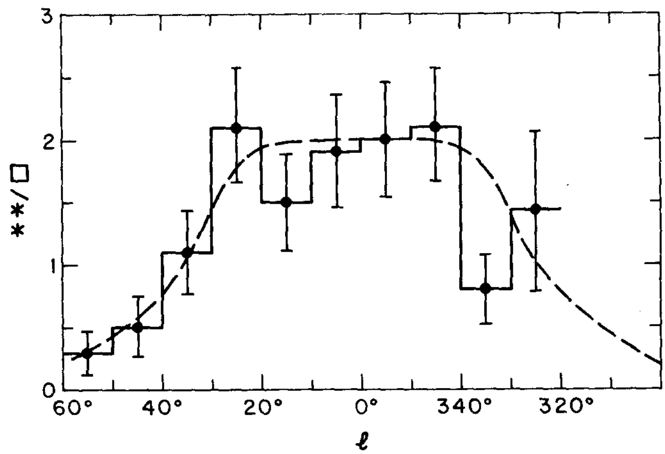

Figure 6. *Surface density distribution of OH/IR stars at $b = 0^{O}$ as a function of galactic longitude. Units in the vertical direction: number of OH/IR stars per square degree of sky.*

A tentative but interesting result has very recently been obtained by Baud (private communication). He suggests that the latitude distribution of stars with $\Delta V < 30$ km s^{-1} is broader than the latitude distribution of stars with $\Delta V < 30$ km s^{-1}. Since ΔV is correlated with period and hence (possibly) with stellar age, this result, if confirmed, may indicate different Z distributions of stars of different ages.

6. Distribution of OH/IR stars in longitude.

Whereas all observers agree about the observed latitude distribution, there is only partial agreement about the observed longitude distribution. It is agreed that in the northern hemisphere a sharp increase in the number density of OH/IR stars occurs when one goes from $\ell = 50^o$ to $\ell = 30^o$, and that at $\ell > 50^o$ very few OH/IR stars exist. In the southern hemisphere the data are less extensive, but also there very few OH/IR stars are found farther than 40^o away from the galactic centre (Goss, private communication). Disagreement exists on the question whether or not at $\ell < 30^o$ the star counts reach a maximum. Johansson et al. (1977b) find an excess of stars around $\ell = 30^o$ and conclude that they are viewing tangentially along a spiral arm. Bowers discovered a few more stars between $\ell = 20^o$ and $\ell = 30^o$ and rejects the excess at $\ell = 30^o$, but concludes that at $\ell < 20^o$ a sharp decline in the star counts accurs. My own impression is that Johansson et al. may have been plagued by small number statistics and that Bowers, in spite of the care that he took, may have overestimated his completeness at small longitudes so that he

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missed more stars at $\ell < 20^{\circ}$ than he thought. In any case let me show my own version of the histogram of the stellar distribution in longitude, based on a larger body of data than either Johansson or Bowers had available. Figure 6 shows the surface density distribution Σ_{ℓ} of OH/IR stars as derived from a combination of several surveys. Σ_{ℓ} is the number of stars per square degree averaged over the area ($\ell \pm 5$, $|b| < 0\overset{\circ}{.}5$). The error lines indicate the variation in Σ_{ℓ} if, instead of N stars N $\pm \sqrt{N}$ stars had been counted within a certain counting area. Figure 6 clearly indicates the sharp rise in Σ between $\ell = 50^{\circ}$ and $\ell = 35^{\circ}$. However, it does not contain any convincing evidence that Σ_{ℓ} is smaller in the interval $30^{\circ} > \ell > 340^{\circ}$ or that an excess of sources exists at $\ell = 30^{\circ}$. Changing the area for star counts to ($\ell \pm 5$, $|b| < 1^{\circ}$) does not alter these conclusions.

Although disagreement exists about the existence of a smaller number of stars at, say, $\ell = 10^{\circ}$ compared to $\ell = 30^{\circ}$, there is a clear agreement between the observers that Σ_{ℓ} does not <u>increase</u> significantly between $\ell = 30^{\circ}$ and $\ell = 10^{\circ}$ - this will turn out to be an important fact.

As in the case of the latitude distribution, the longitude distribution may depend on ΔV. Baud (private communication) has found indications that counts of stars with $\Delta V < 30$ km s^{-1} decrease less steeply from $\ell = 30^{\circ}$ to $\ell = 50^{\circ}$ than counts of stars with $\Delta V > 30$ km s^{-1}. Again this could be an indication of different distributions for stars of different age.

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7. Galactic Density Distribution.

The OH/IR stars spread out over 60° in galactic longitude, yet over only 2° in latitude. This means that they form a very flat distribution with axial ratio not larger than 1/30 (unless the Goldreich/Scoville effect occurs). Since the star counts no longer increase at $\ell < 30^{\circ}$, it follows that, approaching the centre, the volume density of stars in the disk does not increase. The distribution should thus be described as a flat uniform disk. It is possible that near the galactic centre the volume density decreases and the "the disk contains a hole". The reality of the hole will, however, not be easy to establish from star counts only since the effect of the hole on the star counts would be very small. The disk is seen edgewise at about $\ell = 35^{\circ}$ and its radius is thus about 5.7 kpc, if the galactic centre is at 10 kpc. Outside this radius the density decreases. It is surprising to realize that this decrease has to be very steep. I have been trying to fit the decrease in the star counts between $\ell = 30^{\circ}$ and $\ell = 50^{\circ}$ by assuming a flat uniform disk for $R < 6$ kpc and a decrease as R^{-k} for $R > 6$ kpc. The result is that $k \gtrsim 5$! In fact, Figure 6 gives a predicted curve based on three assumptions: (i) all sources are within 12 kpc from us; (ii) the density behaves as ρ = constant for $R < 6.0$ kpc and (iii) $\rho \propto R^{-5}$ for $R > 6.0$ kpc.

A density fall off with k=5 is very steep compared to what is found for other stellar populations in the solar neighbourhood. I will come back to this point in Section 9.

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8. The velocity-longitude diagram.

The measurements of the spectral line shape yield very accurate radial velocities. Based on arguments reviewed by Winnberg I assume that the stellar velocity lies halfway between the two stellar peaks. Since the stars are all at very small latitudes the so defined "stellar velocity" is a measure of the velocity in the galactic plane. Plotting all the radial velocities a velocity-longitude diagram is obtained (Fig. 7). Johansson et al. (1977b) were the first to study such a diagram, although their results were limited to the interval $18^{\circ} < \ell < 51^{\circ}$. Figure 7 is quite similar to a velocity-longitude diagram for planetary nebulae (Minkowski 1964). There are four characteristics of Figure 7, three of which I want to discuss in more detail:

1. At $|\ell| < 90^{\circ}$ most of the dots are contained between the line $V = 0$ and the line that gives the maximum radial velocity, V_{max}, along a line of sight due to circular rotation.

2. There are a few dots that exceed the curve of maximum rotation by considerable amounts - for example OH 39.9 - 0.0 exceeds maximum rotation by 70 km s^{-1}.

3. There are several dots in the range $60^{\circ} > \ell > 5^{\circ}$ with considerable negative velocities.

4. Within 7° from the galactic centre the velocities are evenly distributed around $V = 0$ - in fact in this longitude range $\langle V \rangle \approx 0$.

I will now discuss the first three items in more detail. Item 4 will be discussed in Section 10.

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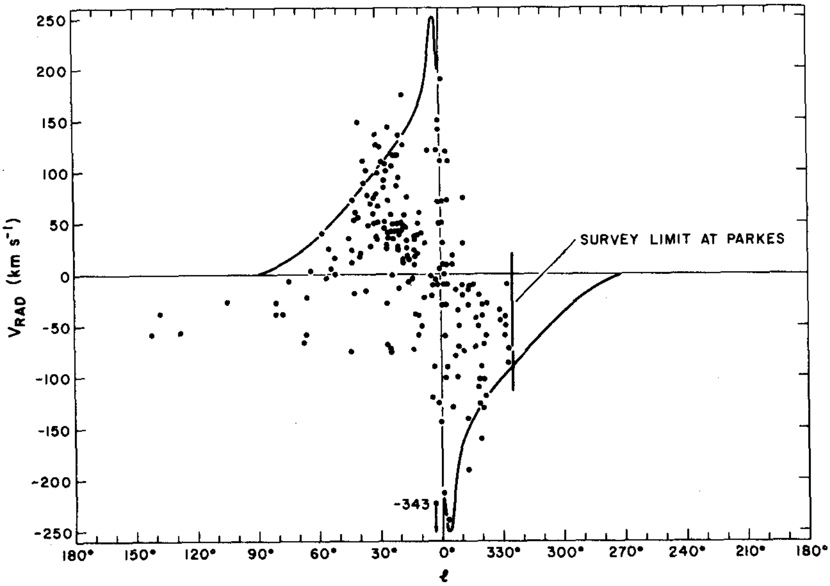

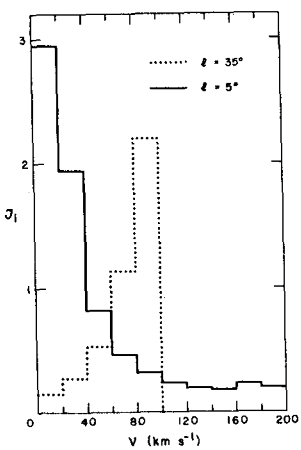

Figure 7. *Distribution of the central velocities of OH/IR stars as a function of longitude and velocity.*

Figure 8. *Model distributions of counts of objects within certain velocity intervals in galactic directions ℓ=35^{O} and ℓ=5^{O}. Model assumes a disk like density distribution and no deviation from circular rotation.*

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Comments on characteristic 1. The fact that most dots are contained between the two indicated lines suggests that the largest part of the radial velocity is caused by galactic rotation. This point is supported by the narrowness of the latitude distribution - unless the Goldreich/Scoville effect (see Section 5) is making the interpretation of this latitude distribution meaningless. Supposing, however, that the z-distribution is actually what it seems to be, we can derive the velocity dispersion σ_z in the z direction from the layer-thickness using the well-known relation $\frac{1}{\rho}\frac{\partial\rho}{\partial z} = \frac{1}{\sigma_z^2} K_z$ (Oort, 1964, eq. (23); Ogorodnikov, 1965, eq. (5.89)). Here ρ is the stellar density, for which we assume the following relation: $\rho = \rho_o$ (R) exp $(-z^2/h^2)$. $K_z = -\alpha(R).z$. For small z both α and ρ depend only on R, the distance from the centre of the Galaxy. We thus obtain the relation $\sigma_z{}^2 = \frac{1}{2}\alpha(R)h^2$. Using a rather conventional galactic model (Miyamoto and Nagai, 1975) I estimate $\alpha = 2.514 \times 10^{14} cm^2 s^{-2} kpc^{-2}$ at R = 4 kpc. From the discussion in Section 5 I estimate h $\leq$ 0.1 kpc, and hence σ_z = 11 km. Analysis of stellar motions in the solar neighbourhood teaches us that σ_Θ and $\sigma_R \gtrsim (2$ to $3)\sigma_z$, so that the velocity dispersion in the direction along the line of sight is expected to be of the order of 20 to 35 km s^{-1}, small compared to the velocity due to galactic rotation. This rough value of σ_R and σ_Θ agrees quite nicely with the value of 30 km s^{-1}obtained by Johansson et al. in a manner to be described below.

It is worthwhile to determine whether the galactic density distribution obtained from the longitude dependence of the star counts (Section 6) agrees with the distribution of dots in Figure 7. This can be done easily if we assume that the velocity of a star equals the galactic rotation velocity V_r plus a random velocity given by a gaussian probability distribution with dispersion σ - provided that $\sigma \ll V_r$. Since $\sigma \approx 30$ km s^{-1} this assumption seems justified. Using methods well known from galactic 21 cm line studies I have predicted counts of stars $J_i(\ell)$ along a certain line of sight in direction ℓ and in radial velocity intervals $(V_{i-1}, V_i) = (0, 20$ km $s^{-1})$, $(20, 40$ km $s^{-1})$, $(40, 60$ km $s^{-1})$ etc. All counts J_i are determined up to one common scale factor. For the density distribution in the galactic plane I assumed $\rho = \rho_o$ for $R < 6$ kpc and $\rho = \rho_o(6/R)^5$ for $R > 6$ kpc, where ρ_o is unknown.

The results for $\ell = 10^o$ and $\ell = 35^o$ are shown in Figure 8. They can be compared directly with Figure 7. I have made only a qualitative comparison, but already the agreement looks quite good. At $\ell = 35^o$ it is predicted that most stars will be close to maximum rotation, at $\ell = 10^o$ they will be close to $V = 0$. Both effects are clearly seen. In Figure 8 it has been assumed that $\sigma = 0$. If σ is not zero (and it is not), Figure 8 has to be modified by folding the curve with a gaussian with dispersion σ. The folding will broaden the distribution and produce non-zero counts at $V < 0$ and above the line of maximum rotation. In fact, stars are observed in these regions. Reasoning of a similar kind led Johansson et al. to determine σ to be ≈ 30 km s^{-1} - in good agreement with the value estimated above from σ_z.

Instead of comparing Figure 7 with the theoretical curves of Figure 8, we may as well compare it with an observed diagram for a galactic ingredient with a similar density distribution: ionized hydrogen. See Figure 9 where the ionized hydrogen distribution has been obtained by Lockman (1976). The conclusion is the same as before: most stars fall inside the boundaries of the H II velocities, but

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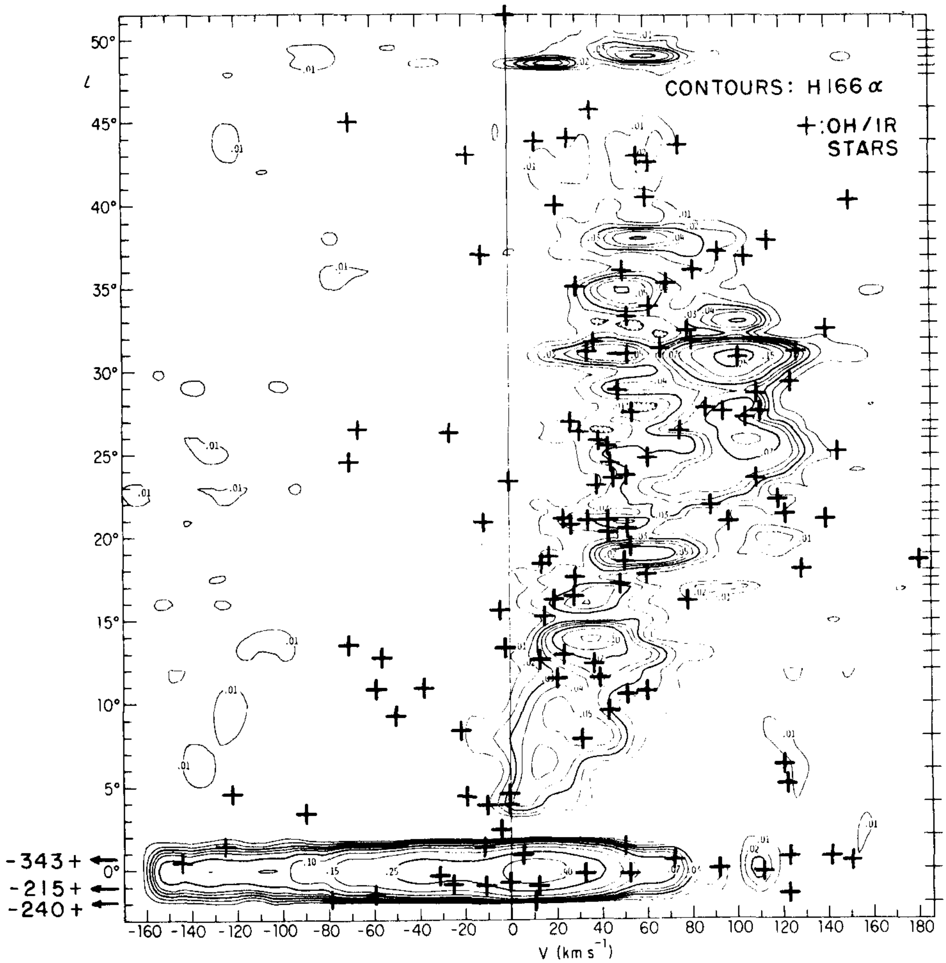

Figure 9. *Distribution of unidentified OH/IR stars compared with the distribution of H 166α emission according to Lockman (1976).*

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there are a few remarkable exceptions.

Finally, nobody has yet taken into account the fact that random deviations from circular motions always imply a systematic deviation in the θ-direction - i.e. if random deviations from circular rotation occur, then the average velocity in the θ-direction (θ_o) is significantly smaller than circular rotation (θ_c).

Comments on characterictics 2. and 3. Whereas the distribution of the large majority of the dots in Figure 7 (at least at $|\ell| > 7^o$) can be understood, there are problems with a few stars that fall far outside the interval $V_{max} > V > 0$ - for example OH 39.9-0.0 with $V = V_{max} + 70$ km s^{-1} and OH 44.8-2.3 with $V = -72$ km s^{-1}. The difference between predicted and observed velocity is very large, so that it appears unlikely that the stars happen to be in the high velocity wing of the gaussian random velocity distribution. Then, what are these stars? I have no good answer to this question, but I like to make two remarks. First, the stars at $V < 0$ have significantly larger latitudes than the stars within the range $V_{max} + \sigma > V > -\sigma$. (This is also the reason why these high velocity stars were not detected in the Onsala survey.) The broader distribution can be understood by assuming that also in the z direction their velocity deviations are larger. The stars with negative V also seem to have smaller ΔV's and hence shorter periods. Whether this effect is statistically significant is uncertain. Second, also when one compares the velocity longitude diagram of Figure 7 with that of Figure 9 the anomaly remains very pronounced.

It therefore appears that the stars with large velocity deviations present a puzzle. Whereas most stars in Figure 7 conform to preexisting ideas, a few definitely do not. Tentatively I will call them "high-velocity stars" and I come back to this point in the next section.

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9. Dynamical considerations.

I would like now to discuss the results of Section 7 and 8.

1. The drop-off in density for $R > 6.0$ kpc is dictated by the steep decrease in star numbers between $\ell = 30^{o}$ and $\ell = 50^{o}$ and appears to be quite firmly established. This drop-off ($\rho \propto R^{-5}$) is much faster than for the overall mass distribution in the Galaxy ($\rho \propto R^{-1}$; see e.g. Burton, 1976) or for several stellar populations in the solar neighbourhood ($\rho \propto R^{-3}$; Blaauw, 1964). However, the drop-off agrees quite closely with that of H 166α emission (Lockman as quoted by Burton 1976) and of CO emission (Burton, 1976). Also the overall brightness distribution at 2.4 μm appears to support a similar drop-off (Hayakawa er al., 1977).

2. The distribution in latitude gives an upper limit to σ_z of 10 to 15 km s^{-1}, approximately 1.5 to 2 times smaller than σ (20 to 35 km s^{-1}). That $\sigma/\sigma_z \gtrsim 1.5$ to 2, is in agreement with observations in the solar neighbourhood, but the reason for this anisotropy is not understood. Apparently the anisotropy also exists much farther into the Galaxy. This conclusion is wrong, when the Goldreich/Scoville effect, mentioned in Section 5, is operative.

3. The existence of stars with large deviations (up to 70 km s^{-1}) from galactic rotation provides a puzzle. They may be very old stars since their ΔV, and hence their periods, are rather short. It may also be that they are "average" OH/IR stars that obtained large deviating velocities, e.g. as run-away stars. More detailed study of the IR spectrum of the "high velocity" OH/IR stars may shed light on this puzzle.

4. The H 166α distribution is probably indicative for the distribution of massive, early type stars in the Galaxy. Since this distribution is much more confined to the inner 6 kpc of the Galaxy than either the H I distribution or the lower mass stars, it is tempting to conclude that the OH/IR stars are also relatively high mass stars i.e. they are more related to M supergiants than to M giants. However, the OH/IR stars apparently have acquired a considerable velocity dispersion ($\approx$ 30 km s^{-1}). This leads to the fundamental problem of how quickly stars will obtain random velocities. Stellar encounters do not contribute significantly on a time scale of 10^9 year or less (Chandrasekhar, 1960), but encounters of stars with very massive (> 10^6 $M_{\odot}$) clouds may contribute to this process (Spitzer and Schwarzschild, 1953). Within 6 kpc from the galactic center such clouds do exist (Burton, 1976). Another contributing factor may be that the stars are born in clouds that have just passed a galactic shockwave and hence have a velocity deviating by as much as 15 km s^{-1} from the galactic rotation curve (Roberts, 1972).

Finally, attention should be drawn to the paper by Feast (1963). For stars in his longest-period group (384 days) Feast shows that the velocity dispersions are respectively 38, 48, 21 km s^{-1} for the R direction, the direction of galactic rotation, and the z direction. The OH/IR stars may be variables of still larger periods - 500 to 1000 days. If so, one would expect the dispersions of the random velocities to be even smaller. At first sight, therefore, it would appear that there is no contradiction between the velocity dispersions observed by Feast for the local long period variables and the OH/IR stars closer to the galactic centre.

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III. STARS INSIDE THE CENTRAL REGION OF THE GALAXY

10. Properties and discussion

In the discussion in Section 8 of the velocity-longitude diagram (Fig. 7) it has been noticed that for $|\ell| < 5^{\circ}$ the character of the distribution differs. For $\ell > 5^{\circ}$ the distribution is rather much bound between $V = V_{max}$ and $V = 0$; however, for $|\ell| < 5^{\circ}$ the distribution appears to be symmetric around $V = 0$. In fact, Baud finds that averaged over all stars between $\ell = 7^{\circ}$ and $\ell = 0^{\circ}$ $\langle V \rangle = 0$ km s^{-1}. This, and the fact that the velocity dispersion increases strongly toward $\ell = 0^{\circ}$, are indications that the OH/IR stars are part of the nuclear regions of the Galaxy.

Also the star counts increase. In terms of the surface density Σ_{ℓ} defined in Section 6, $\Sigma_{\ell} = 3.4 \pm 1.0$ between $-2^{\circ} < \ell < +2^{\circ}$, whereas $\Sigma_{\ell} = 2.0 \pm 0.5$ at its peak value around $\ell = 30^{\circ}$. However, the significance of this increase is not clear - the galactic centre results have been obtained with a very large telescope (the Bonn telescope), but are very much hindered by the intense radio source Sgr A and by overlying OH absorption due to molecular clouds near the centre. It is therefore not yet clear to what extent the excess is only an observational selection effect.

The large velocity dispersion close to the centre provides a possible way to verify the mass distribution near the centre. Let us assume for convenience a spherically symmetric mass distribution within 1° or 175 pc from the galactic centre. From the work of Sanders and Lowinger (1972) we take $\rho = AR^{-2}$ in the same region. If also the velocity distribution is isotropic we obtain from the equation $d(\rho\sigma^2)/dR = -\rho\, d\phi/dR$ (ϕ is the gravitational potential) the relation

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$\sigma^2 = 2\pi GA$. Since $\sigma \approx 120 \pm 10$ km s^{-1} (from Fig. 7) we find A = 5.2×10^5 $M_\odot$ pc^{-1}. Sanders and Lowinger find 7.6×10^5 $M_\odot$ pc^{-1} from a much more uncertain consideration of the mass to luminosity ratio in the infrared. The agreement is therefore entirely satisfactory.

Finally I would like to draw the attention to a conclusion reached by Baud (see this colloquium), that near the galactic centre the stars have significantly smaller ΔV's and hence are probably much older than elsewhere in the Galaxy.

IV. SUMMARY

1. Systematic surveys have yielded the discovery of over 200 OH/IR stars. The stars are found mainly within 40° from the galactic centre and within 1° from the galactic plane. The distribution in latitude may have been caused by an observational selection effect.

2. The longitude and latitude distributions, and the velocity-longitude diagram indicate that the stars form a very flat disk of radius 6 kpc and thickness 200 pc; outside 6 kpc the density drops very steeply ($\propto R^{-5}$). A density decrease may also occur close to the galactic centre. The stars participate in galactic rotation but show random deviations from this velocity with a standard mean value of 20-30 km s^{-1} in the plane and 10 to 15 km s^{-1} perpendicular to the plane. A few "high velocity" stars occur with large velocity deviation from galactic rotation (up to 70 km s^{-1}).

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3. Large random velocities occur near $\ell = 0^{\circ}$. This indicates that the stars are actually in the central regions of the Galaxy. The velocity dispersion agrees with what is expected from the mass distribution there and gives independent confirmation of the earlier results. The stars are probably older than the OH/IR stars elsewhere in the Galaxy.

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D I S C U S S I O N of paper by HABING:

BOOTH: How does the flux density of the observed OH emission vary with distance from the galactic centre?

HABING: This problem has not yet been studied, but the observational material is now available, so that it can be done.

SHERWOOD: 1. Schultz et al., 1976, reported the first identification of IR counterparts of OH (OH/IR) sources.

2. The |b| histogram distribution is too narrow for the OH velocity dispersion (30-35 km s^{-1}) and is more typical of that of OB stars (10 km S^{-1}). Therefore, the Goldreich-Scoville effect appears to be supported by the |b| histogram distribution.

WINNBERG: What about if the observed steep decline in the number of sources with galactic longitude is also due to the "Goldreich-Scoville effect"? I recall that the distribution of galactic HII regions is similar to the distribution of OH/IR sources you showed.

HABING: This could be an explanation - it really should be looked into. Our test on the correctness of the model for the longitude distribution of the OH/IR stars is in the theoretical prediction of the l-v diagram. So far the l-v diagram seems to confirm the longitude distribution, but the tests should be carried out much more quantitatively.

PEL: For how many globular clusters do we know that they do not show 1612 MHz emission, and to what flux levels?

HABING: Kerr and Bowers searched a series of globular clusters for OH emission. No emission has been found in any globular cluster searched down to a rather low level.

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